

Study of direct CP in charmed B decays and measurement of the CKM angle γ at Belle

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Abstract

The Belle experiment, running at the KEKB e^+e^- asymmetric energy collider during the first decade of the century, has recorded 770 fb^{-1} of data at the $\Upsilon(4S)$ resonance. A combination of recent Belle results obtained with this sample is used to perform a measurement of the CKM angle γ . We use $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D^*K^\pm$ decays where the D meson (D^0 or \bar{D}^0) decays into $K_S^0\pi\pi$, $K\pi$, KK , $\pi\pi$, $K_S^0\pi^0$ and $K_S^0\eta$ final states and D^* decays into $D\pi^0$ and $D\gamma$. Belle obtains the most precise γ measurement to date, $\gamma = (68_{-14}^{+15})^\circ$.

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1 Introduction

Two angles of the CKM unitarity triangle, β and α , have now been measured with high precision [1]. The determination of the third angle, γ , using $B^\pm \rightarrow DK^\pm$ decays, will require much more data than for the other angles. Its determination is however theoretically clean due to the absence of loop contributions; γ can be determined using tree-level processes only, exploiting the interference between $b \rightarrow \bar{c}u\bar{d}$ and $b \rightarrow u\bar{c}d$ transitions that occurs when a process involves a neutral D meson reconstructed in a final state accessible to both D^0 and \bar{D}^0 decays (Fig 1). Therefore, the angle γ provides a SM benchmark, and its precise measurement is crucial in order to disentangle non-SM contributions to other processes, via global CKM fits. The size of the interference also depends on the ratio (r_B) of the magnitudes of the

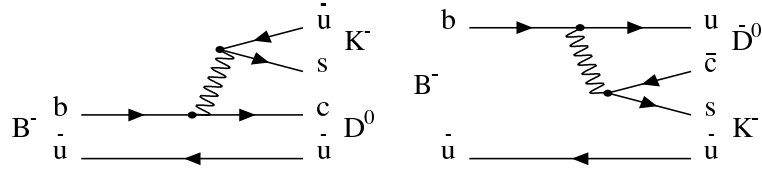


Figure 1: Feynman diagrams for $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow \bar{D}^0 K^-$.

two tree diagrams involved and δ_B , the strong phase difference between them. Those hadronic parameters will be extracted from data together with the angle γ . The value of r_B is the product of the ratio of the CKM matrix elements $|V_{ub}^* V_{cs}|/|V_{cb}^* V_{us}| \sim 0.38$ and the color suppression factor, which result in a value of around 0.1, whereas δ_B can not be precisely calculated from theory. Note that r_B and δ_B can take different values for different B decays: the values of $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D^* K^\pm$ are not the same. Several different D decays have been studied in order to maximize the sensitivity to γ . The archetype is the use of D decays to CP eigenstates, a method proposed by M. Gronau, D. London, and D. Wyler (and called the GLW method) [2]. An alternative approach was proposed by D. Atwood, I. Dunietz, and A. Soni [3]. Instead of using D^0 decays to CP eigenstates, the ADS method uses Cabibbo-favored and doubly Cabibbo-suppressed D decays. In the decays $B^+ \rightarrow [K^- \pi^+]_D K^+$ and $B^- \rightarrow [K^+ \pi^-]_D K^-$, the suppressed B decay is followed by a Cabibbo-allowed D^0 decay, and vice versa. Therefore, the interfering amplitudes are of similar magnitude, and one can expect a large CP asymmetry. The main limitation of the method is that the branching fractions of those decays above are small. A Dalitz plot analysis of a three-body D meson final state allows one to obtain all the information required for the determination of γ in a single decay mode. Three-body final states such as $K_S^0 \pi^+ \pi^-$ have been suggested as promising modes [4] for the extraction of γ . At present the Dalitz method (or GGSZ method) has the best sensitivity to γ .

Latest Belle results using the full data sample taken at the $\Upsilon(4S)$ (corresponding to 772×10^6 $B\bar{B}$ pairs) are described in these proceedings and the resulting γ , combining these different results, is given.

2 GGSZ results

As in the GLW and ADS methods, the two amplitudes interfere if the D^0 and \bar{D}^0 mesons decay into the same final state $K_S^0\pi^+\pi^-$. Assuming no CP asymmetry in neutral D decays, the amplitude for $B^+ \rightarrow D[K_S^0\pi^+\pi^-]K^+$ decay as a function of Dalitz plot variables $m_+^2 = m_{K_S^0\pi^+}^2$ and $m_-^2 = m_{K_S^0\pi^-}^2$ is

$$f_{B^+} = f_D(m_+^2, m_-^2) + r_B e^{i\gamma + i\delta_B} f_D(m_-^2, m_+^2) \quad (1)$$

where $f_D(m_+^2, m_-^2)$ is the amplitude of the $\bar{D}^0 \rightarrow K_S^0\pi^+\pi^-$ decay. Similarly, the amplitude for $B^- \rightarrow D[K_S^0\pi^+\pi^-]K^-$ decay is

$$f_{B^-} = f_D(m_-^2, m_+^2) + r_B e^{-i\gamma + i\delta_B} f_D(m_+^2, m_-^2). \quad (2)$$

The $\bar{D}^0 \rightarrow K_S^0\pi^+\pi^-$ decay amplitude f_D can be determined from a large sample of flavor-tagged $\bar{D}^0 \rightarrow K_S^0\pi^+\pi^-$ decays produced in the continuum e^+e^- annihilation. Once f_D is known, a simultaneous fit to B^+ and B^- data allows the contributions of r_B , γ and δ_B to be separated. The method has only two-fold ambiguity: (γ, δ_B) and $(\gamma + 180^\circ, \delta_B + 180^\circ)$ solutions cannot be distinguished. Due to the fact that r_B is bound to be positive, the direct extraction of r_B , δ_B and γ can be biased. To avoid these biases, the Cartesian coordinates have been introduced, $x^\pm = r_B \cos(\delta_B \pm \gamma)$ and $y^\pm = r_B \sin(\delta_B \pm \gamma)$. A combined unbinned maximum likelihood fit to the B^+ and B^- samples with free parameters (x^\pm, y^\pm) yields the values given in Table 1. Combining $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D^*K^\pm$, the value $\gamma = (78_{-12}^{+11} \pm 4 \pm 9)^\circ$ is obtained [5], where the quoted uncertainties are respectively statistical, systematic and due to an imperfect knowledge of the amplitude model that describes $D \rightarrow K_S^0\pi^+\pi^-$ decays. The last

Table 1: Results of Belle GGSZ analyses.

Observables	$B \rightarrow DK$	$B \rightarrow D^*K$
x^+	$-0.107 \pm 0.043 \pm 0.011$	$+0.083 \pm 0.092 \pm 0.011$
y^+	$-0.067 \pm 0.059 \pm 0.018$	$+0.157 \pm 0.109 \pm 0.018$
x^-	$+0.105 \pm 0.047 \pm 0.011$	$-0.036 \pm 0.127 \pm 0.011$
y^-	$+0.177 \pm 0.060 \pm 0.018$	$-0.249 \pm 0.118 \pm 0.018$

source of uncertainty can be eliminated by binning the Dalitz plot (Refs. [4, 6]),

using information on the average strong phase difference between D^0 and \overline{D}^0 decays in each bin that can be determined using the quantum-correlated $\psi(3770)$ data. Such results have been published recently by CLEO-c [7]. The measured strong phase difference is used to obtain the model-independent result [8], $\gamma = (77 \pm 15 \pm 4 \pm 4)^\circ$, where the last uncertainty is due to the statistical precision of the CLEO-c results.

3 ADS results

For the ADS method, Belle has studied the $B \rightarrow D^{(*)}K$ decays where $D \rightarrow K^-\pi^+$. The observables measured in the ADS method are the ratio of the suppressed and allowed branching fractions:

$$\mathcal{R}_{\text{ADS}} = \frac{\Gamma(B^\pm \rightarrow [K^\mp \pi^\pm]_D K^\pm)}{\Gamma(B^\pm \rightarrow [K^\pm \pi^\mp]_D K^\pm)} = r_B^2 + r_D^2 + 2r_B r_D \cos \gamma \cos \delta, \quad (3)$$

and

$$\mathcal{A}_{\text{ADS}} = \frac{\Gamma(B^- \rightarrow [K^+ \pi^-]_D K^-) - \Gamma(B^+ \rightarrow [K^- \pi^+]_D K^+)}{\Gamma(B^- \rightarrow [K^+ \pi^-]_D K^-) + \Gamma(B^+ \rightarrow [K^- \pi^+]_D K^+)} = 2r_B r_D \sin \gamma \sin \delta / \mathcal{R}_{\text{ADS}}, \quad (4)$$

where r_D is the ratio of the doubly Cabibbo-suppressed and Cabibbo-allowed D^0 decay amplitudes and δ is the sum of strong phase differences in B and D decays: $\delta = \delta_B + \delta_D$. The latest ADS analysis [9] of $B^\pm \rightarrow DK^\pm$ decays with D^0 decaying to $K^+\pi^-$ and $K^-\pi^+$ (and their charge-conjugated partners) uses the full $\Upsilon(4S)$ data sample recorded by the Belle experiment. The signal yield obtained is 56^{+15}_{-14} events, which corresponds to the first evidence for an ADS signal (with a significance of 4.1σ); the ratio of the suppressed and allowed modes and asymmetry are summarized in Table 2. The use of two additional decay modes, $D^* \rightarrow D\pi^0$ and $D^* \rightarrow D\gamma$, provides

Table 2: Results of the Belle ADS analyses.

Mode	\mathcal{R}_{ADS}	\mathcal{A}_{ADS}
$B^\pm \rightarrow DK^\pm$	$0.0163^{+0.0044+0.0007}_{-0.0041-0.0013}$	$-0.39^{+0.26+0.04}_{-0.28-0.03}$
$B^\pm \rightarrow D^*K^\pm, D^* \rightarrow D\pi^0$	$0.010^{+0.008+0.001}_{-0.007-0.002}$	$+0.4^{+1.1+0.2}_{-0.7-0.1}$
$B^\pm \rightarrow D^*K^\pm, D^* \rightarrow D\gamma$	$0.036^{+0.014}_{-0.012} \pm 0.002$	$-0.51^{+0.33}_{-0.29} \pm 0.08$

an extra handle on the extraction of γ as explained in Ref. [10] and illustrated by the predictions of the ADS observables [11] from the values of $(\gamma, \delta_B$ and $r_B)$ obtained with the GGSZ method (shown in Fig. 2). This effect (larger ratio for $B^\pm \rightarrow D^*K^\pm$ with $D^* \rightarrow D\gamma$ and opposite asymmetry between both $B^\pm \rightarrow D^*K^\pm$ channels) is becoming visible in the most recent results from Belle [12].

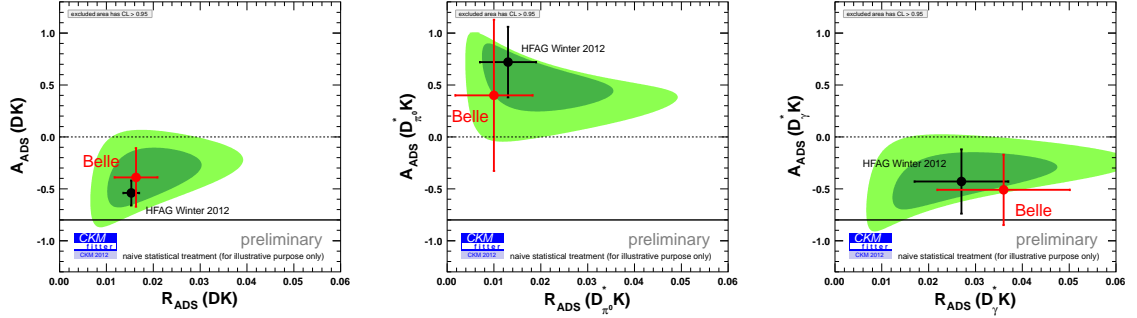


Figure 2: Predictions (from the world averages (γ , δ_B and r_B) values obtained with the GGSZ method) and measurements of the ADS observables for $B^\pm \rightarrow DK^\pm$ (left), $B^\pm \rightarrow D^*K^\pm$ with $D^* \rightarrow D\pi^0$ (center) and $B^\pm \rightarrow D^*K^\pm$ with $D^* \rightarrow D\gamma$ (right).

4 GLW results

As alluded earlier, the other interesting class of modes are the ones where the D^0 decays into CP eigenstates [2] such as K^+K^- , $\pi^+\pi^-$ (CP -even eigenstates) and $K_S\pi^0$, $K_S\eta$ (CP -odd eigenstates). To extract γ using the GLW method, the following observables sensitive to CP violation are used: the asymmetries

$$\mathcal{A}_{CP^\pm} \equiv \frac{\Gamma(B^- \rightarrow D_{CP^\pm} K^-) - \Gamma(B^+ \rightarrow D_{CP^\pm} K^+)}{\Gamma(B^- \rightarrow D_{CP^\pm} K^-) + \Gamma(B^+ \rightarrow D_{CP^\pm} K^+)} = \pm \frac{2r_B \sin \delta_B \sin \gamma}{1 + r_B^2 \pm 2r_B \cos \delta_B \cos \gamma} \quad (5)$$

and the ratios

$$\mathcal{R}_{CP^\pm} \equiv 2 \frac{\Gamma(B^- \rightarrow D_{CP^\pm} K^-) + \Gamma(B^+ \rightarrow D_{CP^\pm} K^+)}{\Gamma(B^- \rightarrow D^0 K^-) + \Gamma(B^+ \rightarrow D^0 K^+)} = 1 + r_B^2 \pm 2r_B \cos \delta_B \cos \gamma \quad (6)$$

Among these four observables, \mathcal{A}_{CP^\pm} and \mathcal{R}_{CP^\pm} , only three are independent (since $\mathcal{A}_{CP^+} \mathcal{R}_{CP^+} = -\mathcal{A}_{CP^-} \mathcal{R}_{CP^-}$). Recently, Belle updated the GLW analysis using their final data sample of 772×10^6 $B\bar{B}$ pairs [12]. These results include the two B decays: $B^\pm \rightarrow D^0 K^\pm$ and $B^\pm \rightarrow D^{*0} K^\pm$, where $D^{*0} \rightarrow D^0 \pi^0$ and $D^0 \gamma$ (the latter modes are shown for the first time in this conference, shown Fig. 5). The signs of the \mathcal{A}_{CP^+} and \mathcal{A}_{CP^-} asymmetries (Eq. 5) should be opposite (as shown by the predictions illustrated in Fig. 4 obtained by the CKMfitter group [11]), which is now confirmed by the Belle experiment (Table 3).

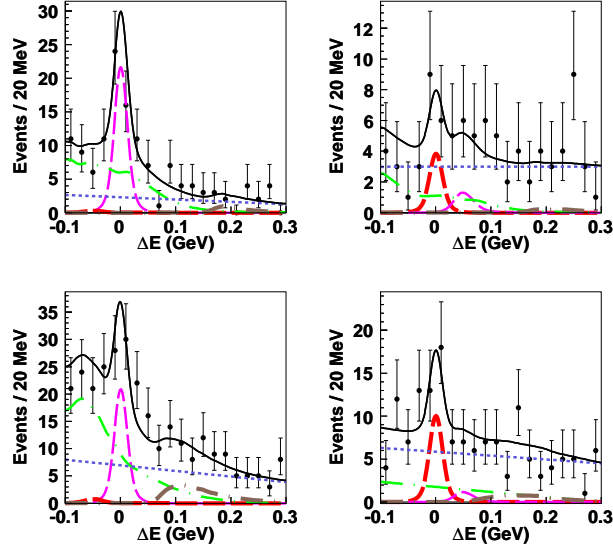


Figure 3: Signal for the $B^\pm \rightarrow D^* h^\pm$ decays from Belle ADS analysis. The plotted variable, ΔE , peaks at zero for signal decays. On the right plots, $[K^+\pi^-]_D K^-$ components are shown (by thicker dashed curves (red)) for $D^* \rightarrow D\pi^0$ (top) and $D^* \rightarrow D\gamma$ (bottom).

5 γ combination from Belle measurements

We combine the available Belle observables of the $D^{(*)}K$ system obtained for the GGSZ method (model-dependent results shown in Table 1), the ADS method (Table 2) and the GLW method (Table 3) using the frequentist procedure also exploited in Ref. [11]. The 1-CL curves obtained with for the angle γ as well as for the hadronic parameters (δ_B and r_B) of $B \rightarrow DK$ mode are shown in Fig. 6 and the 68% C.L. intervals are summarized in Table 4. Belle obtains the most precise γ measurement to date: $\gamma = (68^{+15}_{-14})^\circ$.

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Table 3: Compilation of R_{CP} and A_{CP} results for CP -even and CP -odd decay modes from Belle.

Observables	$B \rightarrow DK$	$B \rightarrow D^*K$
$R_{CP} +$	$1.03 \pm 0.07 \pm 0.03$	$1.19 \pm 0.13 \pm 0.03$
$R_{CP} -$	$1.13 \pm 0.09 \pm 0.05$	$1.03 \pm 0.13 \pm 0.03$
$A_{CP} +$	$+0.29 \pm 0.06 \pm 0.02$	$-0.14 \pm 0.10 \pm 0.01$
$A_{CP} -$	$-0.12 \pm 0.06 \pm 0.01$	$+0.22 \pm 0.11 \pm 0.01$

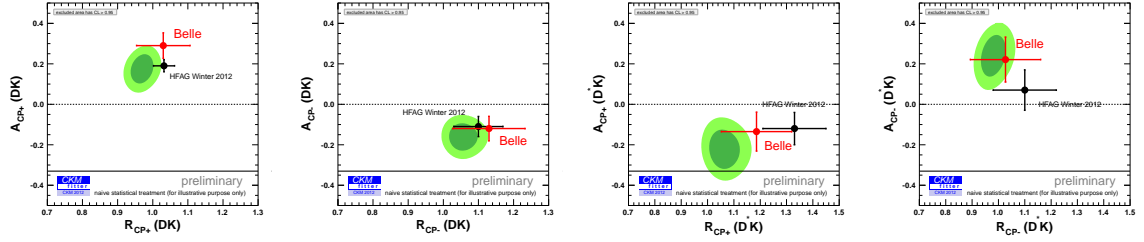


Figure 4: Predictions (from the world averages (γ , δ_B and r_B) values obtained with the GGSZ method) and measurements for the GLW observables for $B^\pm \rightarrow DK^\pm$ (top) and $B^\pm \rightarrow D^*K^\pm$ (bottom).

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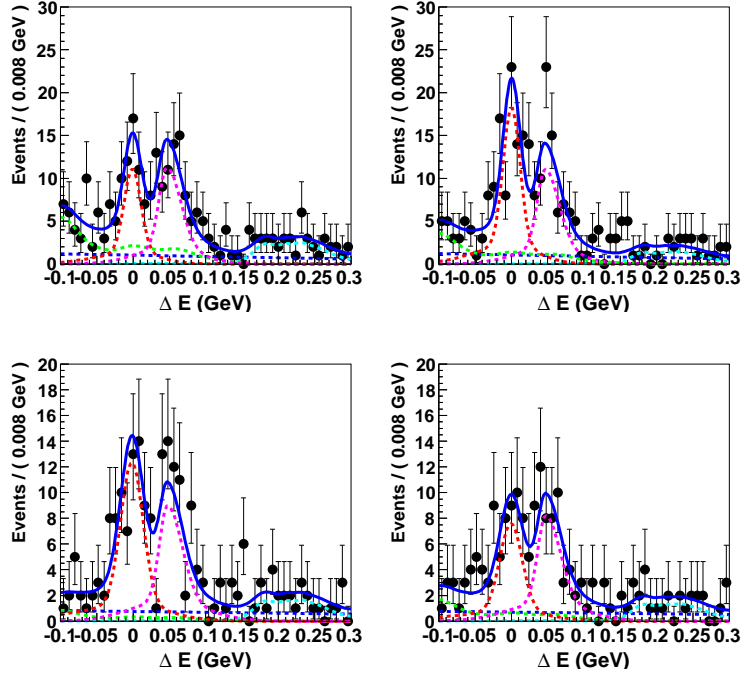


Figure 5: Signals for $B^\pm \rightarrow D^*(D\pi^0)K^\pm$ decays: the left (right) figures are for B^- (B^+) decays and the top (bottom) figures are for CP -even (CP -odd) eigenstates.

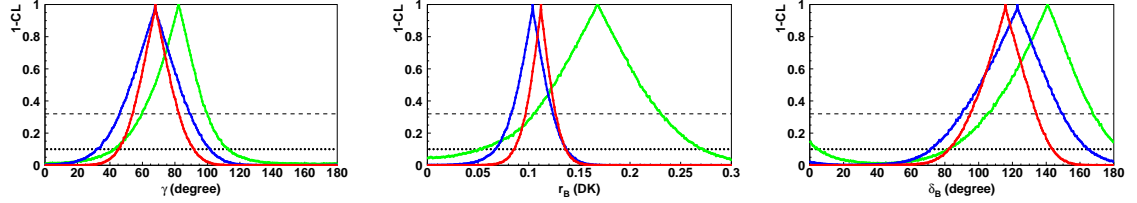


Figure 6: 1-CL curves for γ (left), r_B (center) and δ_B (right) from the Belle $D^{(*)}K$ results. The green curve is for the GGSZ results, the blue for GGSZ and ADS results using δ_D from mixing and CLEO-c measurements, the red for GGSZ, ADS and GLW results.

Table 4: Confidence intervals (68% C.L.) for the angle γ and the hadronic parameters of DK (δ_B and r_B) obtained by the combination of the $D \rightarrow D^{(*)}K$ results of the Belle collaboration.

Method	γ ($^\circ$)	δ_B ($^\circ$)	r_B
GGSZ	82^{+18}_{-23}	141^{+27}_{-36}	$0.168^{+0.063}_{-0.064}$
GGSZ+ADS	68 ± 22	123^{+27}_{-33}	$0.104^{+0.020}_{-0.021}$
GGSZ+ADS+GLW	68^{+15}_{-14}	116^{+18}_{-21}	$0.112^{+0.014}_{-0.015}$